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## Switching of Kerker effect from single $\text{Sb}_2\text{Se}_3$ nanoparticles

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**Abstract.** The Kerker effect is one of the fundamental concepts in nanophotonics for controlling scattered radiation from single nanoparticles. It is based on the interaction of electric and magnetic dipoles, which, as a result of interference, determine the directional pattern of scattered radiation. The implementation of this principle allows the creation of nanoantennas that effectively redirect radiation from other nanoscale sources. This work demonstrates the possibility of dynamically controlling the directional pattern of scattered radiation by using nanoparticles made of the phase-change material  $\text{Sb}_2\text{Se}_3$ . The “ON” and “OFF” modes of directional scattering are shown when the phase of the material changes. These results may open up a new path in the implementation of dynamically changing nanoantennas for applications in quantum cryptography and optical telecommunications.

**Keywords:** nanoparticles, phase change materials, Kerker effect

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Конференционная статья

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## Переключение эффекта Керкера от одиночных наночастиц из $\text{Sb}_2\text{Se}_3$

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**Аннотация.** Эффект Керкера является одной из ключевых концепций современной нанофотоники для управления рассеянным излучением от одиночных наночастиц. Он основан на взаимодействии электрического и магнитного диполей, которые в результате интерференции определяют диаграмму направленности рассеянного излучения. Реализация данного принципа позволяет создавать наномантенны, эффективно перенаправляющие излучение от других наноразмерных источников. В данной работе демонстрируется возможность динамического управления диаграммой направленности рассеянного излучения за счет использования наночастиц из фазопеременного материала  $\text{Sb}_2\text{Se}_3$ . Показан режим «ВКЛ» и «ВЫКЛ» направленного рассеяния при смене фазы материала. Эти результаты могут открыть новый путь в реализации динамически изменяющихся наномантенн для приложений квантовой криптографии и оптической телекоммуникации.

**Ключевые слова:** наночастицы, фазопеременный материал, эффект Керкера

**Финансирование:** Работа выполнена при поддержке РФФ (проект № 25-79-10137).

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## Introduction

Controlling the direction of light propagation using nano-objects is a major achievement in modern nanophotonics. One way to achieve this control is by changing the directional pattern of scattered light from nanoparticles. This is possible due to the realization of the Kerker effect, in which interference occurs between magnetic and electric dipole moments. The Kerker effect was first described in 1983 when observing light scattering from a magnetic particle [1], but later this effect was generalized for non-magnetic particles as well. To date, it has been shown that the Kerker effect can be observed from various nano-objects, including metasurfaces and particles of arbitrary shape [2, 3]. However, as a rule, all implementations of the Kerker effect are static [4], that is, the scattering pattern can only change when the wavelength or size of the nanostructure changes. This imposes significant limitations on the use of nanoparticles as nanoantennas, as it is not possible to dynamically change the pattern.

One solution to the problem of dynamic light control could be the use of phase-change materials [5]. These are a class of materials that undergo a reversible phase transition from an amorphous to a crystalline state. Phase transitions in phase-change materials are realized under the action of a thermal stimulus, which can be created either directly by thermal heating or through the conversion of an electrical or optical pulse into local heat within the material. When the phase of the material changes, its optical and electrical properties also change dramatically. These materials are actively used to create reconfigurable metasurfaces and photonic structures that provide dynamic light control [6]. One of the promising materials in this class that can be used in photonics is  $\text{Sb}_2\text{Se}_3$  (hereafter SbSe) [7]. This is a new wide-bandgap material with no losses in the near-IR range, which distinguishes it favorably from more well-known materials such as GST, AIST, and GeTe [8]. At the same time, the refractive index in both the amorphous and crystalline phases is close to that of silicon. This contributes to further compatibility with silicon photonics components.

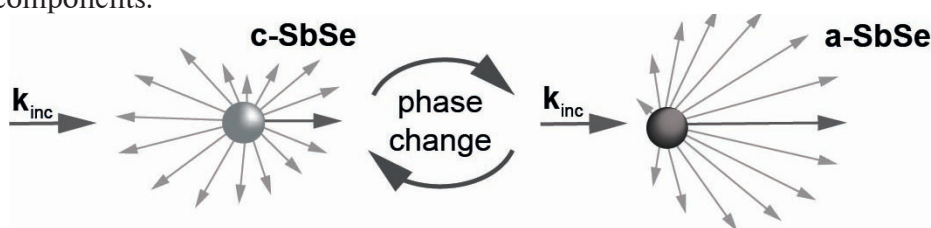


Fig.1. Schematic of the working principle of Huygens metaatom

In our work, we demonstrate the possibility of changing the light scattering diagram for SbSe nanoparticles by changing its phase (Fig. 1). We performed a theoretical calculation of light scattering spectra followed by multipole decomposition from nanoparticles with a diameter of 260–300 nm. We determined the dependence of the spectral position of resonances associated with the electric and magnetic dipole moments in the particle, as well as their spectral shift when the phase of the material changes. As a result of multipole decomposition, spectral regions were determined where electric and magnetic dipole moments of equal intensity are observed, i.e., regions where the Kerker effect can be observed. Finally, scattered light directionality diagrams were constructed, demonstrating the possibility of “ON” and “OFF” directional scattering when the phase of the material changes. These results can serve as a foundation for the creation of tunable nanoantennas for quantum and optical telecommunications applications and photonic computing circuits.

### Materials and Methods

The paper investigates light scattering by a single spherical nanoparticle (metaatom). The scattering cross-section (SCS) of a single metaatom can be expressed in terms of Mie theory:

$$C_{sca} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) (|a_n|^2 + |b_n|^2), \quad (1)$$

where  $k_0$  is the wavenumber in the surrounding medium,  $a_n$  and  $b_n$  are the Mie coefficients corresponding to the electric and magnetic multipole moments, respectively, and  $n$  is the order of multipole.

The Mie coefficients are expressed in terms of Riccati–Bessel functions:

$$a_n = \frac{n_s \Psi_n(n_s x) \Psi'_n(x) - \Psi_n(x) \Psi'_n(n_s x)}{n_s \Psi_n(n_s x) \xi'_n(x) - \xi_n(x) \Psi'_n(n_s x)}, \quad (2)$$

$$b_n = \frac{\Psi_n(n_s x) \Psi'_n(x) - n_s \Psi_n(x) \Psi'_n(n_s x)}{\Psi_n(n_s x) \xi'_n(x) - n_s \xi_n(x) \Psi'_n(n_s x)},$$

where  $n_s$  is the refractive index of the sphere and the Riccati–Bessel functions are:

$$\Psi_n(x) = x j_n(x), \quad \xi_n(x) = x h_n^{(1)}(x), \quad (3)$$

where  $j_n(x)$  is the spherical Bessel function of the first kind,  $h_n^{(1)}(x)$  is the spherical Hankel function of the first kind,  $x$  is the size parameter, defined as  $x = k_0 r$  with  $r$  being the radius of the sphere.

To analyze the contribution of various multipole moments to the scattering of spherical nanoparticles, Cartesian electric and magnetic multipoles were calculated using the COMSOL Multiphysics software package (Electromagnetic Waves, Frequency Domain module).

Cartesian multipoles, defined by the polarization distribution inside the particle, are equivalent to spherical multipoles Mie for arbitrary shapes and spherical particles. The mathematical definition of electric and magnetic dipole moments in Cartesian representation was used in accordance with [9].

Electric dipole moment  $\mathbf{p}$  in Cartesian form is as follows:

$$\mathbf{p} = \int \mathbf{P} j_0(kr) dV + \frac{k_0^2}{2} \int \frac{3(\mathbf{r} \cdot \mathbf{P}) - r^2 \mathbf{P}}{(kr)^2} j_2(kr) dV, \quad (4)$$

where  $\mathbf{P}$  is the polarization vector,  $r$  is the radius vector,  $k$  is the wavenumber in the particle,  $j_0$  and  $j_2$  are spherical Bessel functions.

Magnetic dipole moment  $\mathbf{m}$ :

$$\mathbf{m} = \frac{3i\omega}{2} \int \frac{\mathbf{r} \times \mathbf{P}}{kr} j_1(kr) dV. \quad (5)$$

The cross sections for the scattering of electric and magnetic dipoles were determined as:

$$C_{ED} = \frac{k_0^4}{6\pi\epsilon_0^2 |E_0|^2} \mathbf{p}^2, \quad (6)$$

$$C_{MD} = \frac{k_0^4}{6\pi\epsilon_0^2 |E_0|^2 c^2} \mathbf{m}^2, \quad (7)$$

where  $|E_0|^2$  is the intensity of incident field.

Kerker conditions were used to analyze the radiation pattern. [1]. These conditions are given by:

$$C_{sca}^{forward} \propto |a_1 + b_1|^2, \quad (8)$$

$$C_{sca}^{backward} \propto |a_1 - b_1|^2. \quad (9)$$



The first condition ( $a_1 = b_1$ ) corresponds to maximum forward scattering. The second condition ( $a_1 = -b_1$ ) leads to suppression of scattering in the forward direction and predominant backward scattering.

## Results and Discussion

Let us consider the scattering cross section of a spherical particle in the amorphous and crystalline phases of a material when illuminated by a plane wave (the incident wave vector is directed along the  $x$ -axis). The research particle sizes were investigated: radii  $R = 130$  nm and  $R = 150$  nm in the wavelength range 700–1000 nm. The choice of particle radii is due to the fact that the corresponding dipole resonances lie in the near-infrared and telecommunications range, which makes metaatoms applicable in telecommunications applications. The meta-atom is examined in air ( $n = 1$ ), providing a universal approach to analysing its optical properties. As shown in the article on dielectric nanoparticles [10], the influence of the substrate on the spectral characteristics of the meta-atom depends on its optical properties. For weakly reflective substrates (for example, glass), the primary influence of the substrate is a change in the scattering cross-section amplitude, while the resonance shift remains insignificant. This approach allows us to identify the fundamental resonant characteristics of the material, and the influence of a specific substrate can subsequently be taken into account as a correction for given experimental conditions. In the amorphous phase, pronounced electric and magnetic dipole resonances are observed. The first-type Kerker effect occurs at 1030 nm for a particle with  $R = 130$  nm and for a particle with  $R = 150$  nm at a wavelength of 1393 nm. The scattering is collimated with the propagation of the incident radiation (Fig. 2). The coincidence of the phases of the electric and magnetic dipole moments in the amorphous phase at these wavelengths leads to preferential forward scattering and suppression of reflection. Thus, the amorphous phase exhibits the full behaviour of a Huygens metatom. A change in the particle radius leads to a shift in the spectral position of the electric and magnetic dipole resonances, and therefore also changes the position of their intersection, corresponding to the Kerker condition.

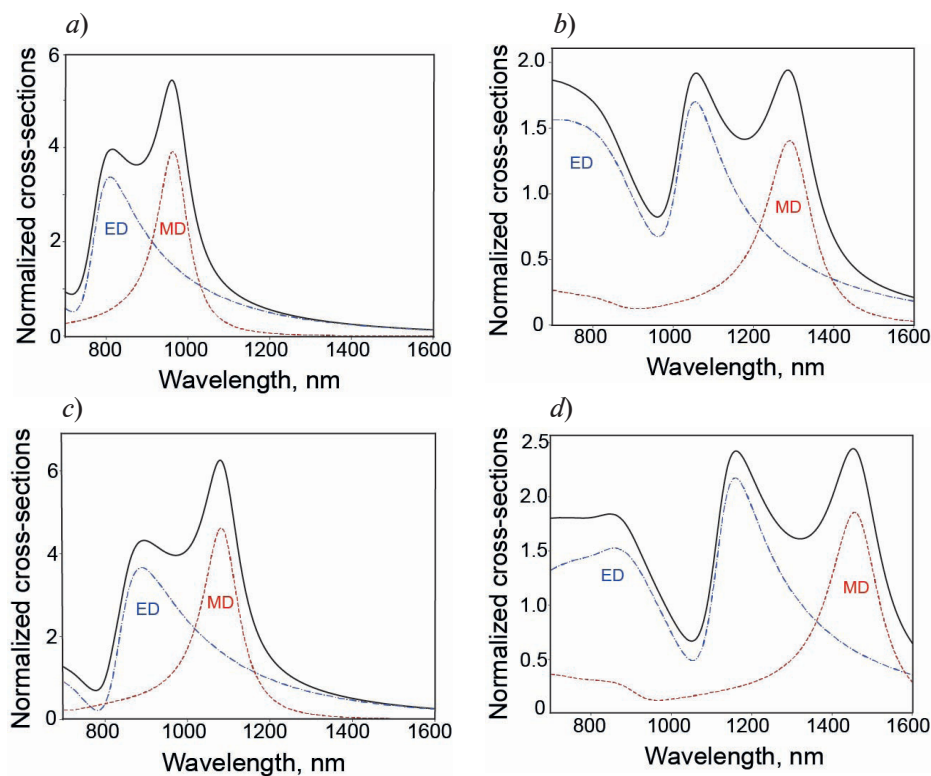


Fig.2. Scattering cross-sections and multipole decomposition for a spherical nanoparticle of (a) amorphous SbSe ( $R = 130$  nm), (b) crystalline SbSe ( $R = 130$  nm), (c) amorphous SbSe ( $R = 150$  nm) and (d) crystalline SbSe ( $R = 150$  nm).

The spectra are normalized to the geometric section of the sphere

The transition to the crystalline state of the material is accompanied by an increase in the absorption of the material and a change in the phase of dipole oscillations. The change in the SbSe phase leads to significant changes in the scattering cross section. At wavelengths of 1030 and 1393 nm, there are no intersections between the electric and magnetic dipoles for the crystalline phase. The far-field scattering distribution at a wavelength of 1030 nm for a particle with a radius of 130 nm confirms these effects (Fig. 3).

These results highlight the potential of dynamic light control through phase state adjustment.

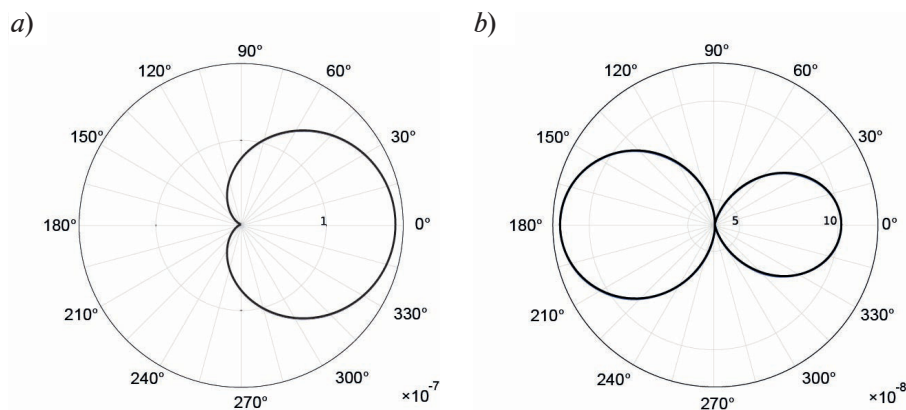


Fig.3. Far-field scattering patterns at wavelengths of 1030 nm, respectively from a single (a) amorphous SbSe nanoparticle and (b) crystalline SbSe nanoparticle

### Conclusion

The work demonstrated that the Kerker effect is observed in the light scattering from a single SbSe nanoparticle. The possibility of dynamic changes in the spectral position of resonances in the scattering spectrum when the phase of the material changes was shown. The possibility of changing the direction of propagation of scattered radiation by changing the phase of SbSe has also been demonstrated. We are confident that the results obtained will find practical application in the creation of reconfigurable nanoantennas for telecommunications, cryptography, and photonic computing circuits.

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